Steady State Analysis of Weapon Charging Systems for EM Guns

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This report documents an analytical approach to determination of weapon charging power as a function of firing duty cycles for electric weapon systems. Though the method neglects transient behavior in the power system components, it does provide approximate figures for the trades in power and energy storage of interest to the vehicle concepts community. Because the exact energy required to defeat a variety of targets using hypervelocity launch and novel projectile concepts is still being researched, the results are presented over a very broad range of energies. This approach also lends itself well to other pulsed loads perceived for implementation in an advanced concept vehicle. The results indicate that consideration of the firing scenarios expected (beyond a simple maximum firing rate) can result in much higher firing rate capability with limited prime power supplies. These firing scenarios will also prove thought provoking for the Army from an operational perspective in planning tactical approaches to most effectively utilize the advantages and avoid limitations of the electric weapon system.

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Steady-State Analysis of Weapon Charging Systems for EM Guns

S. Fish and T. Savoie

Abstract—This report documents an analytical approach to determination of weapon charging power as a function of firing duty cycles for electric weapon systems. Though the method neglects transient behavior in the power system components, it does provide approximate figures for the trades in power and energy storage of interest to the vehicle concepts community. Because the exact energy required to defeat a variety of targets using hypervelocity launch and novel projectile concepts is still being researched, the results are presented over a very broad range of energies. This approach also lends itself well to other pulsed loads perceived for implementation in an advanced concept vehicle. The results indicate that consideration of the firing scenarios expected (beyond a simple maximum firing rate) can result in much higher firing rate capability with limited prime power supplies. These firing scenarios will also prove thought provoking for the Army from an operational perspective in planning tactical approaches to most effectively utilize the advantages and avoid limitations of the electric weapon system.

1.0 Purpose

With the armor community currently assembling plans for the next generation combat vehicle to replace today's main battle tank, studies are being conducted to determine how such a vehicle should fight. This Future Combat System (FCS) will be revolutionary in its technology and capitalize on the lessons learned from Force XXI in operations and deployment of the land force. This study was requested to provide near term guidance to the Armor School, the Army Research Laboratory (ARL), and the Tank-Automotive Research Development and Engineering Center (TARDEC) on the power and energy trade-offs associated with electric weapons. This trade-off information will serve to guide initial system studies examining required power as a function of firing profile. It is hoped that this data will highlight favored modes of firing which can in turn influence potential operational considerations when implementing combat vehicles equipped with these weapons systems. The analysis used considers the weapon system in isolation, and neglects transients in the power system components. This simplification is done to reduce the scope of the parameter space to the zeroth order effects. Though the neglected effects will increase the ratings required for prime power and/or energy storage, their magnitude should be relatively small and is dependent on the overall power system configuration. The resulting trade-offs described in this study nevertheless highlight the fundamental relationships between required charging power and installed pulsed energy storage needed for rather complex firing sequences typically utilized in both direct fire and artillery type applications. More detailed studies using simulations such as POWERSIM[1,2] can then be utilized to fine tune the estimates presented here.

2.0 Analysis

The analysis conducted here is based on steady-state power system performance. The assumptions associated with the steady-state analysis are listed below:

— Power supply can transition from zero power output to full rated power output instantaneously.

— A Pulsed Energy Storage (PES) device is a buffer between the power supply and the weapon, and has sufficient power and pulse shaping capability to drive the weapon at all the considered weapon energy conditions considered.

— The PES has an instantaneous discharge time, but the charger power is considered disconnected for one second during each firing to allow time for isolation, discharge, and reconnection of the power supply.

— Power supply calculations are due only to the energy used for the weapon, but are referenced to equivalent "uninstalled" prime power ratings by imposing an estimated efficiency of 0.75 between the uninstalled machine and the PES.

— Shot energy parameters are referenced to the weapon breech with an efficiency of 0.8 assumed for the discharge of the PES.

Four firing sequences are considered in this study based on the most common specifications considered by the armor community to date. It should be emphasized that real firing sequences are mixtures of all of these types, and that dynamic simulation will allow more detailed examination of these mixes in future studies. It is assumed that the PES is fully charged prior to initiating the firing sequences examined below.

<u>Case 1: Continuous Fire</u>

The first case considered is a continuous firing of rounds with no specified number of rounds. It is a rather simple case to analyze because the minimum required power must be equivalent to the power required to recharge after each shot. Likewise, the minimum energy required is the equivalent shot energy. Figure 1 shows the required power per unit of breech energy as a function of firing rate for this case. The energy store required is only dependent on the energy per shot and the discharge efficiency, is therefore not plotted. A somewhat more illuminating representation of this data is shown in Figure 2, which puts some dimensions to the power over a range of breech energies. Though this configuration allows unlimited shots at or below the specified firing rate, it comes at a high price in required prime power. A prime mover power of 2500 HP or 1.87 MW can only achieve a firing rate of 3.4 rounds per minute if the breech energy is 20 MJ and 6.8 rounds per minute if the breech energy is 10 MJ.

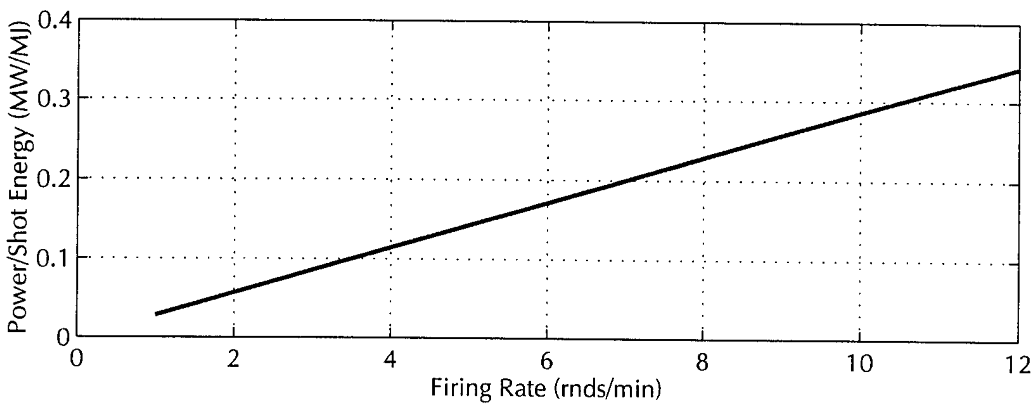


Figure 1. Non-dimensional power for continuous firing.

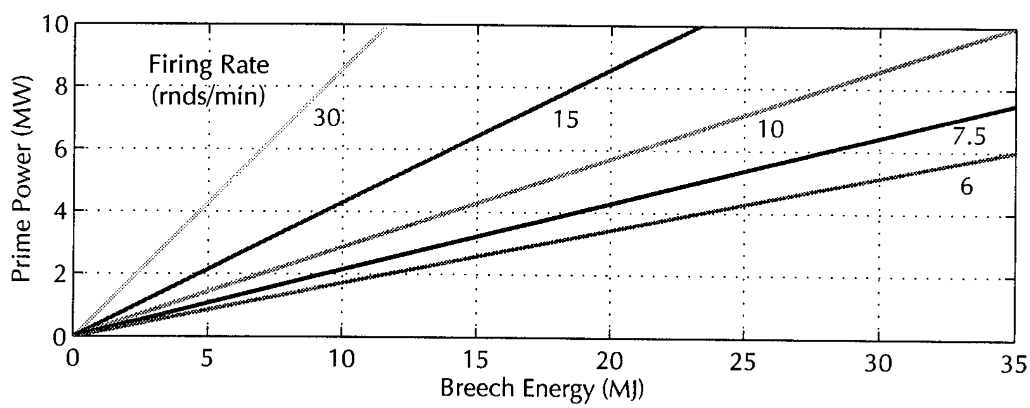
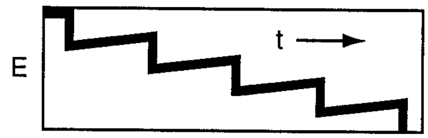


Figure 2. Continuous firing dimensional data.

Case 2: Single Burst

Tanks rarely fire many rounds continuously, however, and the next case studied a singe burst of n rounds followed by a relatively long period of time where the energy storage device may be recharged at an unhurried pace. In this case, we can write the equation for the required prime power based on complete depletion of the PES at the completion of the last shot in the burst:

$$P = \frac{n_s E_{shot} - \eta_d E_{\max}}{\eta_d \eta_c (n_s - 1)(t_s - t_f)} \qquad (1)$$



where: E_{shot} = breech energy per shot

E_{max} = maximum useable energy in PES

t_s = time between shots (inverse of firing rate)

t_f = firing time (charger disconnected)

h_d = discharge efficiency of PES

h_c = charge efficiency of PES

n_s = number of shots fired in the burst

The implications of Equation (1) can be plotted easily if we fix one of the parameters. Figure 3 shows how the power required depends on shot energy and number of shots in the burst which are stored in the PES for a fixed firing rate of 12 rounds per minute. For example, if you have n_s = 4 shots per burst, and you can store $n_s/2$ shots in your energy store, the power required can be determined by the height of the lines at the ordinate corresponding to $n_s/2$. In this case, one can see that as the number of shots stored approaches the number fired in the burst, the required power goes to zero independent of the shot energy (although the absolute capacity of the PES and its resulting size will be proportional to the shot energy). It is therefore simple to determine an estimate of power required for any size single burst. The power values scale linearly with a firing rate as long as $t_f \ll t_s$, which is typical for expected fieldable systems. The case where n_s = 1 corresponds to the trivial case of a single shot fired.

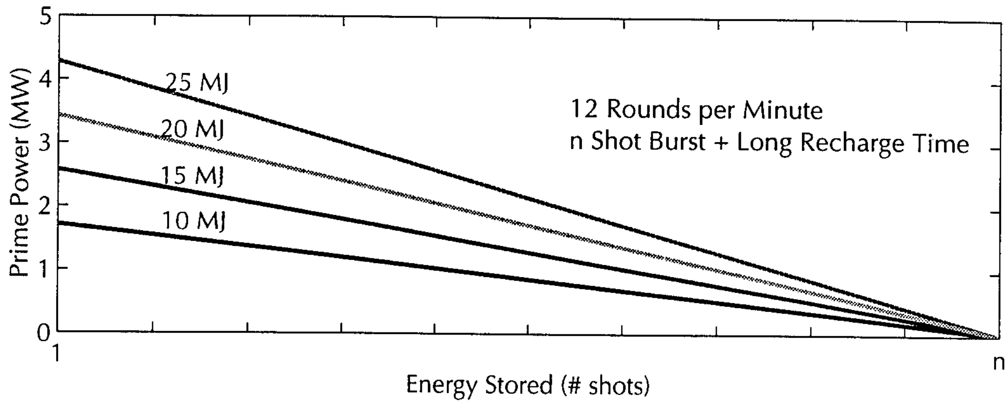


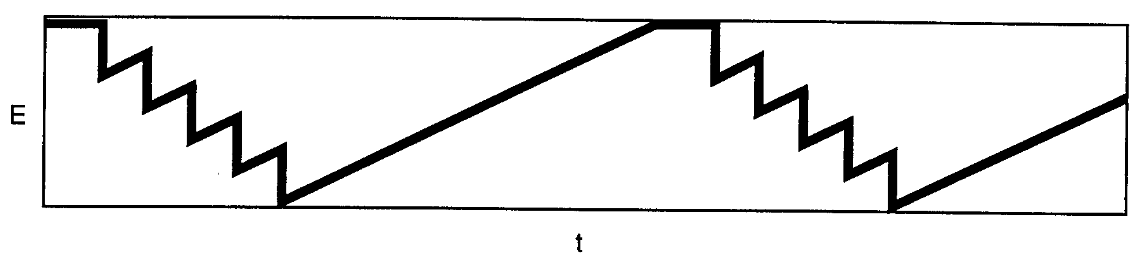
Figure 3. Single burst power requirements (Case 2).

Case 3: Infinite Sequence of Bursts

We can next refine Case 2 to include the recharge time between bursts and assume that this burst sequence is continued for a long time. In this case, the power source must supply the energy for all shots in the burst, but may do so over the period including both the shooting and between burst times. The result is a further reduction in required power. The equation for the minimum required power in this case is given by the following equation:

$$P = \frac{n_s E_{shot}}{\eta_d \eta_c [(n_s - 1)(t_s - t_f) + t_b]} \tag{2}$$

where: t_b = time between bursts



The minimum PES required under conditions defined by Equation (2) can be derived by knowing that the PES is completely discharged in the last shot of each burst. This relationship is found in Equation (3) in a form which allows examination independent of shot energy and number of shots per burst:

$$\frac{E_{\max}}{n_s E_{shot}} = \frac{1}{\eta_d}\left[1 - \frac{(n_s - 1)}{(n_s - 1) + \frac{t_b}{t_s}}\right] \tag{3}$$

where, we again assume $t_f << t_s$.

Figure 4(a) shows a plot of Equation (2) as a function of E_{shot} and for t_b varying from 0 to 60 seconds. This plot highlights impact of the time between bursts on prime power. The number of shots fired per burst in Figure 4(a) is 2, with 5 seconds between shots.

(a)

(b)

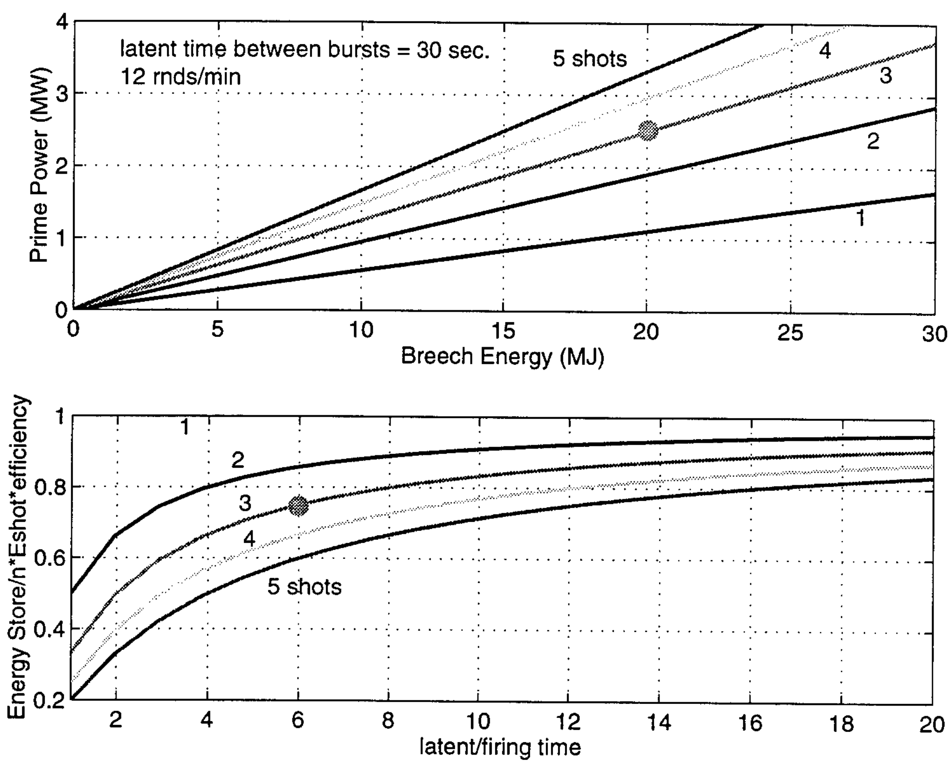


Figure 4. Power and energy requirements for many bursts as a function of shots per burst.

The PES minimum associated with the 2 shot burst conditions given in Figure 4, and calculated using Equation (3) are plotted in Figure 4(b). Although this plot shows a decrease in energy as t(b) is decreased, it must be realized that the power being required is being increased as given by Equation (2) and shown in Figure 4(a).

Take an example case: MJ Breech energy shots
3 shot bursts
12 rounds per minute (assumed in Figure 4)

The prime power required for weapon charging (from the spot on Figure 4(a)) is 2.5 MW. The energy storage required for this case is determined from Figure 4(b). If we assume that there is 30 seconds between the last shot of each burst and the first shot of the next burst (the latent time between bursts), and the firing time is 1/firing rate = 5 seconds, then the latent/firing time is 30/5 = 6. From Figure 4(b), with 3 shots per burst, we get (from spot) a value of 0.75 for the energy storage ratio. To then get the actual value of the energy required, we multiply this 0.75 times the total stored energy we would have required for a single burst if there had been no recharge (3 shots * 20 MJ/shot / discharge efficiency). In this case (discharge efficiency = 0.8) one would get a required stored energy of 56 MJ.

Optimization of the power/energy trade-off under these circumstances must be made based on other factors such as minimizing total volume claim by the combined power supply and PES.

Case 4: Finite number of bursts

When we confine the number of bursts, there is potential to further reduce the required power for a given burst size, although this reduced power comes at a penalty in increased PES capacity (see Figure 5). The relationship between power and PES (E_{max}) is described by Equation (4):

$$P = \frac{n_s n_b E_{shot} - \eta_d E_{\max}}{\eta_d \eta_c [(n_s - 1) t_s n_b + (n_b - 1) t_b]} \tag{4}$$

where n_b = number of bursts.

It is assumed that the PES is depleted after the last shot of the last burst, and that sufficient time is available before the next shot sequence to recharge sufficiently to execute it. Figure 6 shows that for the following conditions, breech energy = 20 MJ and PES = 80 MJ, the reduction in required power as the number of bursts is reduced. Note that the benefit of designing for a reduced number of bursts (versus the solution from Case 3) is significant for three and fewer bursts. Case 3 results, though they require slightly higher charging power levels, typically result in significantly smaller PES's and also have the benefit of not being as operationally restrictive as Case 4. For example, the prime power required for 3 bursts of 3 shots (Case 4) under the same firing and latent time constraints is 12% less than if we design for an infinite number of bursts (Case 3). The size of the energy store was increased 42% from 56 MJ (Case 3) to 80 MJ (assumed in this Case 4 exercise). In addition, after the 9th shot, the weapon would require a period of 12 seconds before firing a single shot, and 36 seconds before being able to repeat the same 9 shot sequence again.

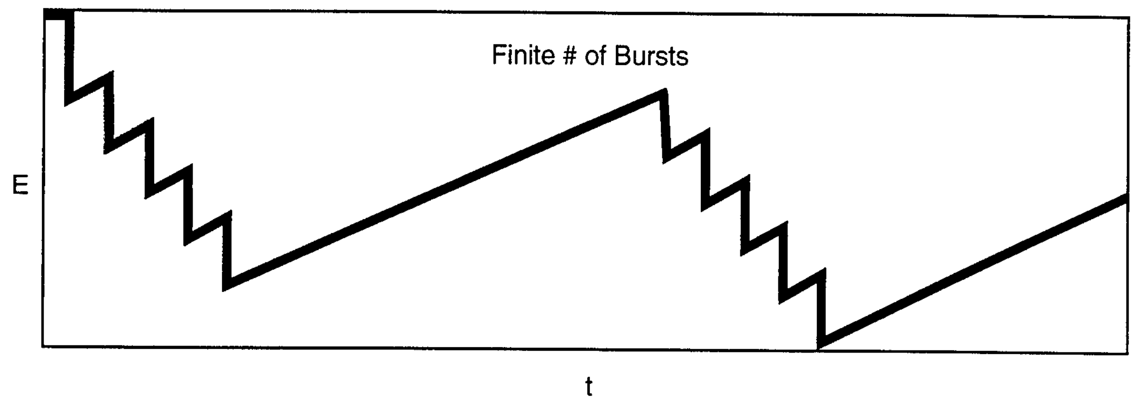


Figure 5. Energy history for finite number of bursts.

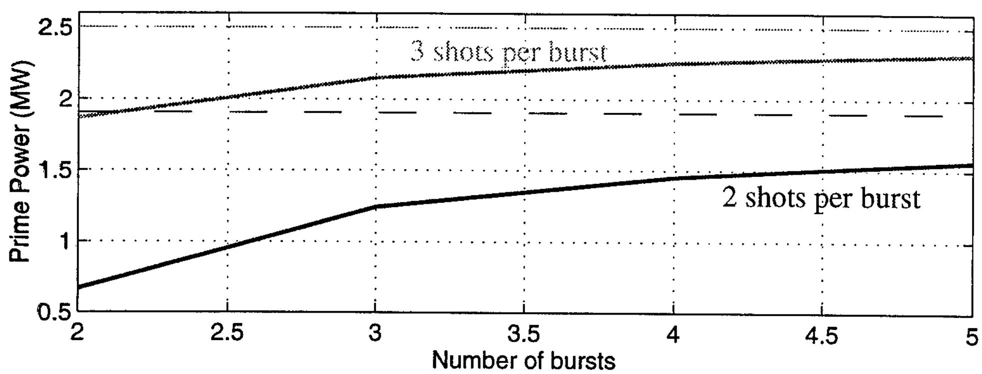


Figure 6. Power requirements for finite number of bursts.

3.0 Discussion

The above case studies highlight the basic relationships between equivalent prime power and pulsed energy storage (PES) required for charging a weapon system. It should be noted that the analysis done was of a steady state nature. Although it allows for a finite time for discharge of the PES when no charging can be done, it does not include effects due to transient power buildup and decline. These transient periods play an important role particularly when the firing rates are high, and when the time between bursts are short. The influence of slow response of an engine/generator combination can be mitigated. However, with smart use of intermediate energy stores, which have near the same power capability, can be operated in parallel with the main engine. Proper energy management of the whole power system is critical for this functionality, and can be developed further with more detailed dynamic simulations. However, a couple of important trends can be developed from the studies done here.

First, one can see from the comparison of Cases 1 and 2, that there is a tremendous benefit in power reduction when utilizing some form of energy storage which can accommodate multishot bursts. This benefit is increased as the number of shots per burst is decreased and the time between bursts is increased. These obvious points are not new, but have been quantified to allow the trades to be more intelligently made. A comparison of Cases 3 and 4 indicate that further reductions in prime power requirements can be realized by looking at a limited number of bursts, by accepting somewhat larger percentage increases in energy storage. Where the optimum point lies in these cases will depend on densities of prime power and energy storage technologies available at the time. Careful analysis can also indicate what the time penalties are for looking at finite burst fire sequences as was done in Case 4.

Operationally, this indicates that the weapon system power supply can be most significantly reduced by selectively firing and resting, rather than getting involved in a continuous firing situation. The implications for this characteristic are that the vehicle will greatly benefit from coordinated fires with additional vehicles where each covers the other during movement. This form of operation, practiced today, will become easier and more important as improvements in reconnaissance and situational awareness improves with digital communications. In addition, the importance of shot energy is clear for all the firing sequence results, and hence an additional benefit can be realized in kill rate by adapting the shot energy to each specific target. In other words, by reducing the energy shot at light targets like armored personnel carriers, one can fire more rounds in a given period and thus increase the rate of kills. This flexibility, not available with conventional cannons, is a cornerstone in the push towards EM guns for higher performance combat systems.

Acknowledgments

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